

1 Introduction

The exploration of the inner structure of the nucleon is of fundamental importance. Two decades have passed since the European Muon Collaboration (EMC) at CERN discovered that the spins of the quarks and anti-quarks in the proton provide only an unexpectedly small fraction of the proton's spin [1]. This finding, which became famously known as the “proton spin crisis”, implies that the spins of the gluons or orbital angular momenta of the partons must contribute significantly to the proton spin, or both. To advance our understanding of the spin structure of the nucleon is the primary objective of the RHIC spin physics program. Its major goals are to determine the gluon spin contribution to the proton spin, to elucidate the flavor structure of the valence and sea quark polarizations in the proton, and to explore high-energy spin phenomena arising for transverse proton polarization. As this report will show in detail, significant achievements have been made at RHIC toward these goals. Commensurate with these, there have been major advances in theory. In the following, we introduce the key objectives of the RHIC spin program, highlighting the progress that has been made, at RHIC and on the associated theory.

Measurement of the gluon spin contribution to the proton spin. Key to this is to measure the spin-dependent gluon distribution $\Delta g(x, Q^2)$,

$$\Delta g(x, Q^2) \equiv g^+(x, Q^2) - g^-(x, Q^2) , \quad (1)$$

where g^+ (g^-) denotes the number density of gluons with the same (opposite) sign of helicity as the proton's, at gluon momentum fraction x . We have indicated the dependence on the hard “resolution” scale Q at which the gluon is probed. QCD quantitatively predicts the variation of Δg with that scale. The integral of Δg over all momentum fractions gives the gluon spin contribution to the proton spin,

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx . \quad (2)$$

$\Delta g(x, Q^2)$ may be probed in inelastic high-energy scattering with polarized protons. This is exploited in the spin program at RHIC, where one considers reactions with final states produced at large transverse momentum (p_T). As we described in the RHIC Spin Plan [2], spin asymmetries for these may be interpreted in terms of the polarized parton distribution functions, among them Δg , and short-distance interactions of the partons. Thanks to the asymptotic freedom of QCD, the latter can be calculated in QCD perturbation theory. Using these calculated partonic cross sections, the parton distributions can be extracted from the experimental measurements of spin asymmetries.

Large efforts have been made over the past few years to obtain the first-order (or, “next-to-leading order (NLO)”) QCD corrections to the spin-dependent partonic scattering cross sections relevant for the RHIC spin program, and for the measurement of Δg in particular [3]. This program is very advanced. The calculations for single-inclusive reactions such as $pp \rightarrow \pi X$ and $pp \rightarrow \text{jet} X$, which have so far been used by the RHIC experiments to constrain Δg , have been completed. The attention is now shifting to less inclusive final states, such as di-jets or hadron pairs, following the path taken by the RHIC experiments. The viability of the perturbative-QCD approach has been established at RHIC by the successful quantitative comparison of measurements for the spin-averaged cross sections with the theoretical NLO calculations.

Published RHIC results [4, 5] indicate that the gluons in the proton are relatively little polarized; complementary results from lepton scattering made by the HERMES and COMPASS experiments [6] are consistent with this. Recent precision RHIC data collected during Run 6 [7, 8] close in on the spin-dependent gluon distribution Δg over a significant range in momentum fraction x of the gluon.

A new global analysis of the RHIC cross section and asymmetry data and inclusive and semi-inclusive DIS data has been introduced. This analysis treats the directly measured data in a model-independent way, at next to leading order in QCD perturbation theory. This analysis [9] is an important theoretical advance, involving use of Mellin moments and Monte-Carlo sampling. Quark, anti-quark, and gluon polarized distributions in the proton have been obtained. The combined data set places a strong constraint on Δg . The gluon spin distribution turns out to be small in the region of momentum fraction $0.03 \lesssim x \lesssim 0.2$ accessible at RHIC. It is not yet possible to make a statement about the full integral over all $0 < x < 1$, the gluon spin contribution ΔG . This will require to constrain $\Delta g(x, Q^2)$ at lower x than so far accessible. It is not ruled out that there are significant contributions to ΔG from $x < 0.02$ or so. Measurements at RHIC's higher pp center-of-mass energy of 500 GeV, and coincidence measurements for production at forward angles, will be important for reaching lower x , as discussed later in this document.

Measurements of the flavor patterns of quark and anti-quark polarizations in the proton.

It has long been recognized that W boson production at RHIC, which is predicted to be 100% parity-violating, provides access to the individual polarizations of the quarks and anti-quarks in the colliding protons that form the W bosons. The u - and d -quark polarizations have been measured in DIS, while the *anti* - u - and *anti* - d - quark polarization measurements will be the first direct measurements. The goal is to understand the details behind the small average polarizations measured for the $(q + qbar)$ spin contributions to the proton spin, as measured by DIS. Indeed, interpretation of polarized inclusive DIS results on the small contribution of the $(q + qbar)$ spin contribution to the proton spin, suggest a large negative strange quark polarization in the sea. Indeed, the new global fit to the RHIC and DIS data suggest a flavor asymmetry in the sea, with a node in the strange quark polarization vs. strange quark momentum fraction. It is already known that the *anti* - d - quark density in the unpolarized proton is significantly larger than the *anti* - u - quark density, observed in DIS and Drell-Yan measurements. The W boson measurements at RHIC will explore both the unpolarized and polarized differences in light flavor-separated anti-quark densities and polarizations, directly and with precision for the first time.

The flavor structure of the nucleon sea explores fundamental aspects of strong-interaction dynamics. Models of nucleon structure generally make clear predictions about the flavor asymmetry in the sea. These predictions are often related to fundamental concepts such as the Pauli principle. For example, since u quarks in the proton are primarily aligned with the proton spin while d quarks carry opposite polarization, one finds from considerations based on Pauli-blocking the qualitative expectations $\Delta \bar{u} \geq 0$, $\Delta \bar{d} \leq 0$ [10]. Arguments based on the limit of a large number of colors in QCD suggest that the flavor asymmetry in the nucleon should be larger in the polarized than in the spin-averaged case, $|\Delta \bar{u} - \Delta \bar{d}| > |\bar{u} - \bar{d}|$ [11]. Chiral quark models of the nucleon make quantitative predictions for the sea quark polarizations [12].

Dedicated measurements of the quark and anti-quark polarizations can be performed in semi-

inclusive DIS by tagging definite hadrons in the final state. Data have been obtained by the SMC, HERMES, and COMPASS collaborations [13] and are included in the global analysis discussed above. Within relatively large uncertainties, they give a first indication that the pattern $\Delta\bar{u} \geq 0$, $\Delta\bar{d} \leq 0$ may indeed be realized in nature [9].

Clean and elegant measurements of up and down quark and anti-quark polarizations will be possible in RHIC's 500 GeV program by studying the production of W^\pm bosons. Here one uses the violation of parity in weak interactions, which manifests itself in the W^\pm bosons coupling to only left-handed quarks and right-handed anti-quarks, and thus provides a natural probe of polarization. In addition, the scale in these interactions is set by the large W mass, where the perturbative-QCD theoretical framework is solid and reliable, more so than in the present and forthcoming semi-inclusive DIS measurements. We shall discuss the possibilities offered by W production at RHIC in detail in this document, and also the challenges that are involved.

It turns out that the main information to be obtained at RHIC will be on the \bar{u}, \bar{d} anti-quark polarizations at medium momentum fraction, $0.04 \lesssim x \lesssim 0.15$, and on the u, d quark polarizations in the valence region $x \gtrsim 0.2$. The latter probe the presence of non-vanishing orbital angular momentum components in the nucleon wave function [14]. The measurements at RHIC in this regime will thus offer interesting comparisons with those performed at the Jefferson Laboratory [15], but at much higher scales. Ultimately, all the W production data from RHIC will be included in the global analysis, so that the best possible information can be extracted. The tools for this are largely in place.

Studies of transverse-spin phenomena in QCD.

At the same time that we observe small or zero helicity asymmetries in our measurements sensitive to the gluon polarization, large spin asymmetries are observed at RHIC for production of π and other hadrons in the forward direction from the polarized beam, for transversely polarized protons colliding with unpolarized protons. The RHIC results, demonstratively in the hard scattering perturbative regime of pQCD, along with results from DIS, and from quark-anti-quark production in e^+e^- collisions, have led to a renaissance of transverse spin, with many new experimental results, and major advances in the theoretical treatment, based on pQCD.

Single transverse spin asymmetries were investigated recently in semi-inclusive hadron production $eN^\uparrow \rightarrow e\pi X$ in deep-inelastic scattering [17, 18], and for proton targets remarkably large asymmetries were found also here. The STAR [19], PHENIX [20] and BRAHMS [21] collaborations have presented data for single-inclusive hadron production. Large single-spin effects at forward rapidities were observed at RHIC energies, a finding that has been a milestone for this field. In fact, new surprises have emerged from the RHIC measurements: detailed studies by STAR [19] have shown an unexpected transverse-momentum dependence of the asymmetry in $pp \rightarrow \pi^0 X$.

The value of single-spin asymmetries lies in what they may tell us about QCD and the structure of the proton. Much progress has been made in our conceptual understanding of single-spin phenomena in recent years. Particular focus has been on a class of parton distribution functions known as ‘‘Sivers functions’’ [22], which express a correlation between a parton's transverse momentum, and the proton spin vector. They therefore contain information on orbital motion of partons in the proton. Theoretical studies have found that the Sivers functions are not universal in hard-scattering reactions [23, 24, 25]. Their non-universality has a clear physical origin that may

be viewed as a rescattering of the struck parton in the color field of the remnant of the polarized proton. Depending on the process, the associated color Lorentz forces will act in different ways on the parton. In deep-inelastic scattering (DIS), the final-state interaction between the struck parton and the nucleon remnant is attractive. In contrast, for the Drell-Yan process it becomes an initial-state interaction and is repulsive. As a result, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two reactions [23, 24, 25]. Beyond color-singlet processes, the non-universality manifests itself in more complex, but calculable, ways. It has been predicted [27] that the sign change with respect to DIS also occurs in $pp \rightarrow \gamma \text{ jet } X$ through the dominant Compton process. For “pure-QCD” processes such as $pp \rightarrow \text{jet jet } X$, initial-state and final-state interactions tend to counteract [28]. Even though there are still outstanding theoretical issues that remain to be addressed, this feature may explain in part why STAR found asymmetries consistent with zero in this channel [29].

The prediction of non-universality of the Sivers functions is fundamental and rooted in the quantum nature of the interactions. It tests all our concepts for analyzing hard-scattering reactions, and its verification is an outstanding challenge in strong-interaction physics that has become a top priority for the world-wide hadronic physics community. Given that Sivers-type single-spin asymmetries have been observed in semi-inclusive DIS [17, 18], the challenge is on now for pp scattering at RHIC to provide definitive tests.

Another important focus of transverse-spin physics is “transversity”. The transversity parton distributions, introduced in [30, 31], measure the transverse polarization of partons along or opposite to the transverse proton spin. Differences between transversity and the helicity distributions discussed earlier give information about relativistic effects in the nucleon [31]. The transversity densities also determine the fundamental tensor charge of the nucleon [31, 32]. The peculiar chiral-odd nature of transversity, which is responsible for much of its physics, has made experimental determinations elusive so far. Only recently has it become possible to combine measurements of Collins-type single-spin asymmetries in lepton scattering [17] with dedicated determinations of the Collins fragmentation functions in e^+e^- annihilation [33], to obtain a first glimpse at the valence transversity distributions [34]. Transversely polarized pp scattering at RHIC offers access to the transversity distributions. Two fragmentation effects, the Collins mechanism and Interference Fragmentation, provide excellent probes. We will discuss these planned measurements in this document.

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